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Cost and Performance Report

(CP-9509)

Plasma Arc Destruction of DoD Hazardous Waste

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COST & PERFORMANCE REPORT
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LIST OF ABBREVIATIONS AND ACRONYMS

ARDEC	Armaments Research and Development Engineering Center
CFR	Code of Federal Regulations
CINCLANTFLT	Commander-in-Chief, Atlantic Fleet
cm	centimeter
CNRMA	Commander, Naval Region Mid-Atlantic
DRE	destruction and removal efficiency
DRMO	Defense Reutilization and Marketing Office
EA	Environmental Assessment
EIS	Environmental Impact Statement
EO	Executive Order
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
eV	electron volts
FIT	factory inspection test
FY	fiscal year
HW	Hazardous waste
kg	kilogram(s)
kW	kilowatt
lb	pound(s)
MACT	Maximum Achievable Control Technology
MMCEMS	multimetals continuous emissions monitor system
NASA	National Aeronautics & Space Administration
NEPA	National Environmental Policy Act
NESHAPS	National Emissions Standards for Hazardous Air Pollutants
NRL	Naval Research Laboratory
NSN	Naval Station Norfolk
PACT	Plasma Arc Centrifugal Treatment
PAHWTS	plasma arc hazardous waste treatment system
PLC	programmable logic controller
PPC	primary processing chamber
PWC	Public Works Center

LIST OF ABBREVIATIONS AND ACRONYMS (continued)

RCRA	Resource Conservation and Recovery Act
RD&D	Research, Development and Demonstration
RFP	request for proposal
RPM	revolutions per minute
STC	secondary treatment chamber
TACOM	Tank and Automotive Command
TCA	Trichloroethane
TCLP	Toxicity Characteristic Leachate Procedure
USACHPPM	U.S. Army Center for Health Promotion and Preventive Medicine
USC	United States Code

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

Naval Station Norfolk (NSN) is the world's largest naval installation and the home of the United States Atlantic Fleet. Activities at the installation generate approximately 3,000,000 lb (1,400,000 kg) of both hazardous and nonhazardous industrial waste annually. Significant components of the waste stream include used paint, cleaning rags, cleaning compounds, and other chemicals used in industrial operations. While the Navy has disposed of these wastes in accordance with environmental regulations, concern exists regarding continuing federal liability for the hazardous waste (HW) once it leaves the installation because the cost is significant. Packaging, off-site transfer, and landfill disposal by private firms under contract to the Navy cost well over $3 million annually.

In the mid-1990s, NSN began exploring alternative methods to dispose of its HW in order to reduce costs and to limit federal liability for the waste after it left the base. At that time, the Naval Research Laboratory (NRL), Washington, D.C., was conducting investigations into the application of thermal plasma technology for destroying simulated Navy shipboard waste. In 1995, NSN and NRL discussed the possible application of plasma arc technology for destroying the HW generated at the Naval Station. These discussions led to a jointly sponsored proposal to the Environmental Security Technology Certification Program (ESTCP) to demonstrate and validate plasma arc technology as a viable method for treating HW generated at the Naval Station. The project was approved in the summer of 1995. Plasma arc technology, which utilizes the very high temperatures generated in thermal plasmas, was developed more than 25 years ago by the National Aeronautics & Space Administration (NASA) to simulate reentry temperatures and has been used for more than 20 years in the metallurgical processing industry. Since the late l980s, it has been investigated as an alternative to incineration for destroying hazardous materials.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objectives of this project were to (1) design, construct, and test a plasma arc hazardous waste treatment system (PAHWTS) that would demonstrate the complete destruction of HW generated at NSN on a production basis; and (2) obtain the operational data needed to establish the effectiveness of plasma arc technology (specifically cost-effectiveness and appropriate feed rates of the waste). It was necessary to follow appropriate National Environmental Policy Act (NEPA) procedures by conducting either an Environmental Impact Statement (EIS) or an Environmental Assessment (EA) and obtaining appropriate air emission and hazardous waste treatment permits. The PAHWTS was designed, constructed, and briefly tested at the site of the contractor who built the system, a draft EA was completed, and an air emission permit to construct the system was obtained from the State of Virginia. However, the system was never installed at NSN because the Commander, Naval Region Mid-Atlantic (CNRMA), decided to withdraw from the original commitment to support the installation and operation at NSN.

1.3 REGULATORY DRIVERS

Emissions from the PAHWTS could consist only of particulate-free gases and a vitrified solid slag. The PAHWTS had to comply with 40 Code of Federal Regulations (CFR) Part 63 (National

Emission Standards for Hazardous Air Pollutants), 40 CFR Part 50 (National Primary and Secondary Ambient Air Quality Standards), 40 CFR Part 60 (Standards of Performance for New Stationary Sources), and 40 CFR Part 264 [Environmental Protection Agency (EPA) Regulations for Owners and Operators of Permitted Hazardous Waste Facilities — Subpart O]. Slag generated by the PAHWTS had to pass EPA's toxicity characteristic leachate procedure (TCLP) test for all TCLP materials.

1.4 DEMONSTRATION RESULTS

Under a contract issued by NRL, Retech Systems LLC designed, constructed, and placed the PAHWTS into operation at their site. Operational testing of the system (designated the factory inspection test) was conducted in October 1999 and included six separate 2- or 3-hour runs on soil, epoxy paint, latex paint, and methanol mixed with 1,1,1 trichloroethane (TCA), in the ratio of 3.5:1. The feed rates for these materials ranged from 300 to 500 pounds (135 to 225 kg) per hour. For the epoxy paint, both liquid and solid materials were fed simultaneously into the primary processing chamber. Stack emissions of CO, NOx, and total hydrocarbons were monitored using continuous emissions monitors and, in each case, the emissions were below the standard limits covered by the National Emissions Standards for Hazardous Air Pollutants (NESHAPS) for HW incinerators. Stack emissions for particulates, metals, dioxins/furans, and HCl were measured in accordance with standard EPA sampling methods. For all runs, the particulates and metals were well below the NESHAPS emissions limits. For the soil and epoxy paint, the dioxins/furans and HCl were below the limits; however, for the methanol/ TCA and latex paint runs, the emissions for the dioxins/furans and HCl exceeded the emission limits. The destruction and removal efficiency for the TCA exceeded 99.9999%. A second operational test was conducted in March 2000 that involved oily rags contained in metal cans fed at an average rate of 200 lb (91 kg) per hour.

A separate economic analysis for operation of the PAHWTS as a full production system at NSN was performed by TAMS Consultants, Inc. They obtained information related to operation of similar plasma arc systems and factored in the processing rates for the PAHWTS and labor rates for Norfolk. They constructed a number of scenarios involving potential reductions in the types and amounts of different types of HW at NSN. Over a 15-year operating period, the net savings of using the PAHWTS instead of the current off-site disposal method ranged from a low of $14 million to a high of $29 million. The projected payback period for the $9.4 million capital costs ranged from 7 to 10 years. The estimated HW treatment cost was reduced from an average of $1.50 per lb ($3.30 per kg) to approximately $0.95 per lb ($2.10 per kg).

1.5 STAKEHOLDER/END-USER ISSUES

Since the PAHWTS was successfully constructed and tested (on a very limited basis), an EA was completed (although a 'finding of no significant impact' was not issued), and a permit to construct was issued by the State of Virginia. It was clear that the system could have been put into operation at NSN had the Commander agreed to fulfill the original commitment. Based on the operation of plasma arc systems at other locations on similar waste streams and the very favorable economic analysis conducted for the NSN system, there was the expectation of successful operation at the Naval Station. In general, the principal end-user issue will almost certainly be convincing to the public that this is a different process from incineration — one that produces fewer and safer emissions.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Plasma is considered representative of the fourth state of matter, the other three being solids, liquids, and gases. A plasma can be described as a gas to which a specific amount of energy has been added to separate the gas component molecules (or atoms, in the case of inert gases) into a collection of ions, electrons, charge-neutral gas molecules or atoms, and other species in varying degrees of excitation (such as free radicals). Depending on the amount of energy added, the resulting plasma can be characterized as thermal or nonthermal.

In a thermal plasma, enough energy is introduced for the plasma constituents to be in thermal equilibrium, i.e., the ions and electrons are, on average, at the same temperature. An electrical arc is one example of a thermal plasma, a manifestation of which is a lightning bolt bridging the gap between a storm cloud and the earth. The temperature of the electrons and ions in thermal plasmas is generally between 0.5 and 1.5 electron volts (eV), with 1 eV associated with a gas temperature of 11,873°C (21,400°F). Generating an electrical arc requires two electrically conducting bodies at different electrical potentials in relative proximity, with a gaseous medium between the bodies at or near atmospheric pressure. Instantaneous electrical discharges are encountered in real life fairly often, as in lightning mentioned above, or just the discharge encountered between one's hand and a doorknob when the relative humidity is very low and the human body picks up a static electrical charge. Sustaining a thermal plasma requires a power supply that can provide continuous current while maintaining the voltage difference between the electrically conducting electrodes. A significant amount of heat is generated with continuous plasma arcs or electrical discharges because of the finite resistance of the plasma. For example, the resistance of a 10-cm long, 100 kW plasma arc is approximately 1 ohm. If sufficient current is forced to pass through the plasma, there is resistive heating as when excess current is forced through a copper wire conductor. Because the conductor is a gas, it cannot "melt" so extremely high temperatures can be achieved. The thermal temperature inside a high-power plasma arc is generally between 6,000 and 20,000°C (10,830 and 36,000°F).

A nonthermal plasma is one in which the mean electron energy, or temperature, is considerably higher than that of the bulk-gas molecules or atoms. Because energy is added to the electrons instead of the ions and background gas molecules, the electrons can attain energies of from 1-10 eV, while the background gas remains at ambient temperature. This nonthermal condition can be created at both atmospheric and subatmospheric pressure. The Aurora Borealis is a naturally occurring nonthermal plasma, and there are numerous examples of artificial nonthermal plasmas, such as fluorescent lights. In these cases, light is generated with very little heat.

In terms of waste treatment, nonthermal plasmas have been used for destroying certain types of toxic or hazardous gases, where the ions, electrons, free radicals, and radiation in the plasma cause chemical reactions to occur that break down the molecules. If the proper conditions are maintained in the plasma, the atoms from the decomposed toxic gas molecules can combine with other atoms and molecules to produce benign species that can be exhausted. There have been examples of nonthermal plasmas being used to destroy emissions from diesel engines. For the treatment of waste such as municipal solid waste, which consists of a wide variety of inorganic and organic materials, the heat from thermal plasma is required. There are numerous examples of the design and

construction of thermal plasma waste treatment systems [1-7], but that is beyond the scope of this report. As with nonthermal plasmas, there are ions, electrons, free radicals, and radiation present in thermal plasmas. However, in each example noted, the thermal plasma has been used only as a heat source to melt and vitrify inorganic materials as well as to pyrolyze and (usually) combust organic materials.

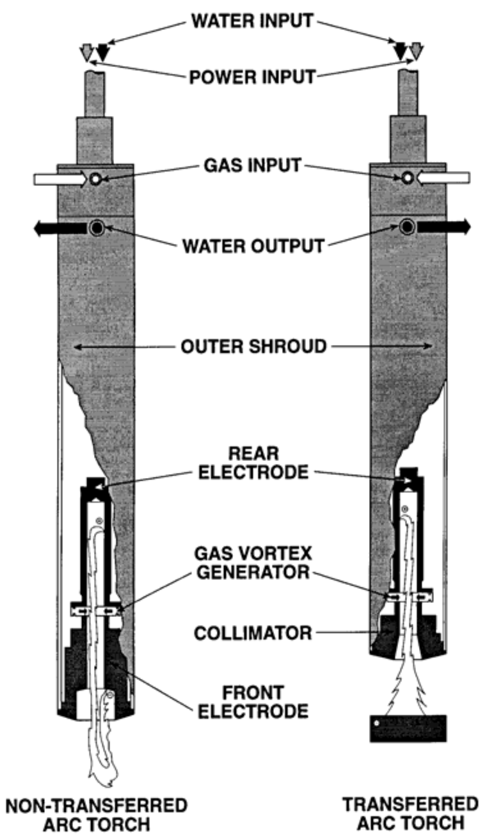

Figure 1. Illustration of the Two Types of Plasma Arc Torches.

The device that is generally used to generate thermal plasma in a controlled reactor is the plasma torch which, in its most simplistic configuration, is nothing more than a cylinder containing one or two water-cooled electrodes. There are two principal categories of water-cooled direct current plasma torches, classified by their operating modes — transferred arc and non-transferred arc — and illustrated in Figure 1. The transferred arc design contains only one electrode in the torch, with the material being processed as the other electrode. These types of torches form the heart of plasma-arc melters, which have been used for decades for industrial-scale refining of metals. For waste treatment, these types of torches would only be used if a substantial percentage of the waste was inorganic material that would not volatize. If the waste is non-conducting at room temperature (e.g., contaminated soil), then generally an electrical conductor such as a graphite liner or sacrificial metal is used with the material, with the arc initially established between the torch and the conductor. The heat generated by the plasma then melts the waste material, generating a molten pool, which becomes electrically conducting. Then the plasma is allowed to transfer directly to the waste, accelerating the vitrification process because heating is caused by radiation from the plasma and from the electron current passing directly into the waste material. If the inorganic material being treated contains sufficient glass formers, such as soil or sand, a slag is formed which, when cooled, will encapsulate heavy metals. Slag formed in this manner generally passes all leaching tests, including the standard EPA TCLP test. Therefore, it is expected that this product would remain stable for geologically long periods of time, indicating that it could be disposed of in standard landfills. There is also the possibility that there would be commercial uses for the vitrified slag such as roadbed aggregate.

The non-transferred arc plasma torch has both electrodes inside the torch; therefore, the energy is dissipated in the gas phase as opposed to the transferred arc torch where some of the energy is dissipated by resistance heating of the condensed phase (i.e., the material being treated). Even though both electrodes are inside the torch body, the plasma extends beyond the end of the torch because of the high gas flow through the torch. These types of torches are most appropriate for treating organic wastes, especially if they are in liquid form. In this case, there is no molten slag pool formed, and the heat from the plasma is used to pyrolyze the organic constituents. Usually, oxygen is introduced into the processing chamber either as a pure gas, as air, or as steam, in order

to oxidize the carbon. If the system is operated in a pure pyrolysis mode, large quantities of carbon black are produced that can contaminate the chamber and interfere with operation. In general, when treating organic materials, the goal is to convert as much of the materials to a gaseous state and produce as little solid residue as possible. Quite often, a secondary treatment chamber is required to ensure complete oxidation of the carbon to carbon dioxide. In this case, the principal constituents exiting the primary processing chamber are CO and H_2, and the principal constituents exiting the secondary processing chamber are CO_2 and H_2O.

2.2 PROCESS DESCRIPTION

Figure 2 is a schematic of the system as constructed by Retech Systems LLC. Note that the footprint of the system is 80 feet (24 meters) by 90 feet (27 meters) and the height of the system (top of the torch pylon and not including the stack) is approximately 45 feet (13.5 meters). The system was designed to meet the specifications established by NRL and to fit within Building LP-24 at NSN. This system is generally referred to by Retech as a PACT-8 system, with PACT indicating Plasma Arc Centrifugal Treatment and the number 8 that the primary chamber is 8 feet (2.4 meters) in diameter. In a PACT system, there is a rotating centrifuge inside of the primary processing chamber which ensures adequate mixing of the molten slag during processing.

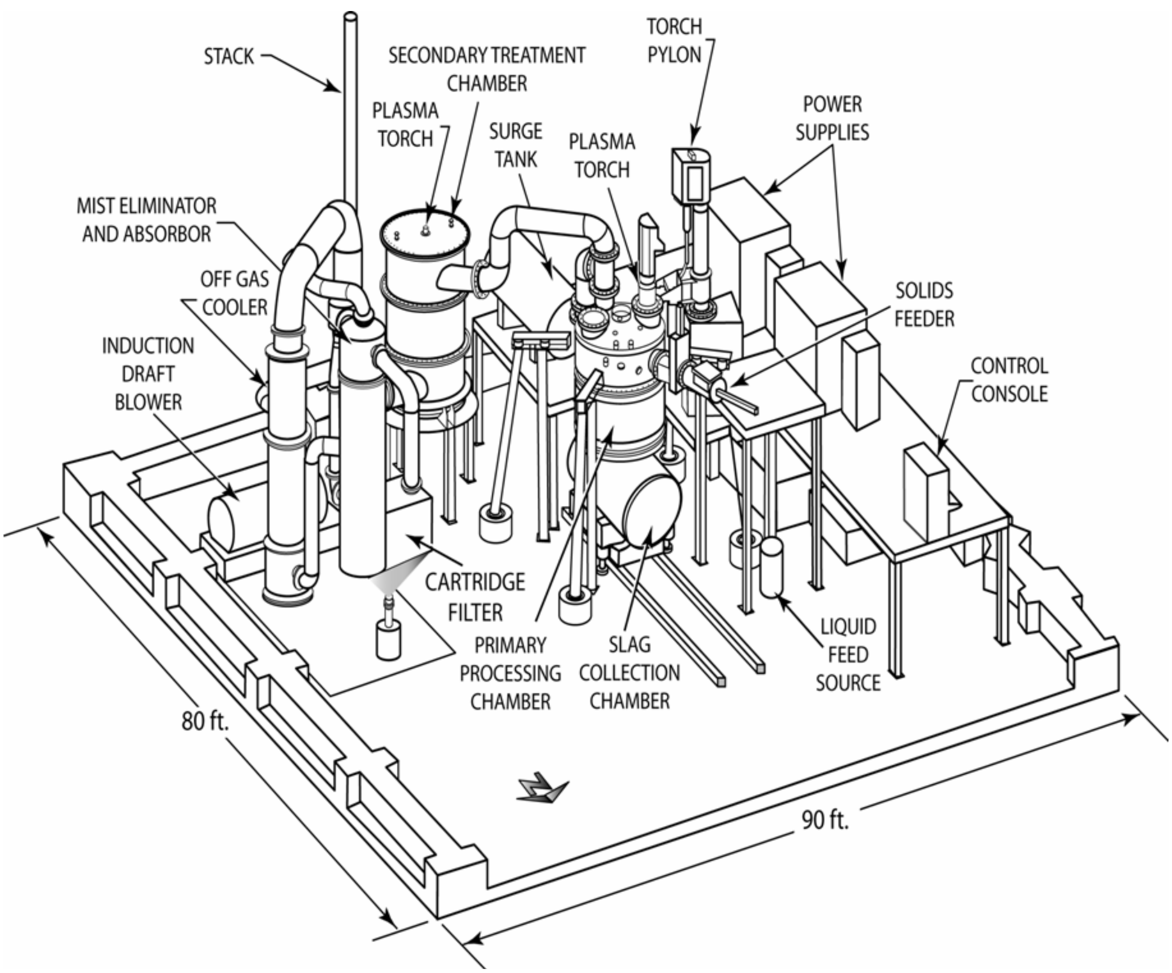

Figure 2. Schematic of PAHWTS. (Note that a substantial portion of the decking is not shown in order to completely show the system components.)

The flow diagram for the PAHWTS is shown in Figure 3. The PAHWTS is designed to accept both process material in pails up to a 5-gallon (19-liter) capacity and bulk solids; in both cases this material is conveyed via a feed screw into the primary processing chamber (PPC). Solids up to the size of the pails are processed through a shredder and into the feed screw which meters the waste into the PPC; liquid waste from the pails is typically predrained into 55-gallon (208-liter) drums prior to shredding. Bulk solids are dumped directly into the feed screw which conveys the material into the PPC. Liquid waste from drums is pumped into a liquid transfer vessel. The combined liquid waste in the liquid transfer vessel is then pumped in a metered fashion to the PPC. Empty drums are sent to be cleaned and reused.

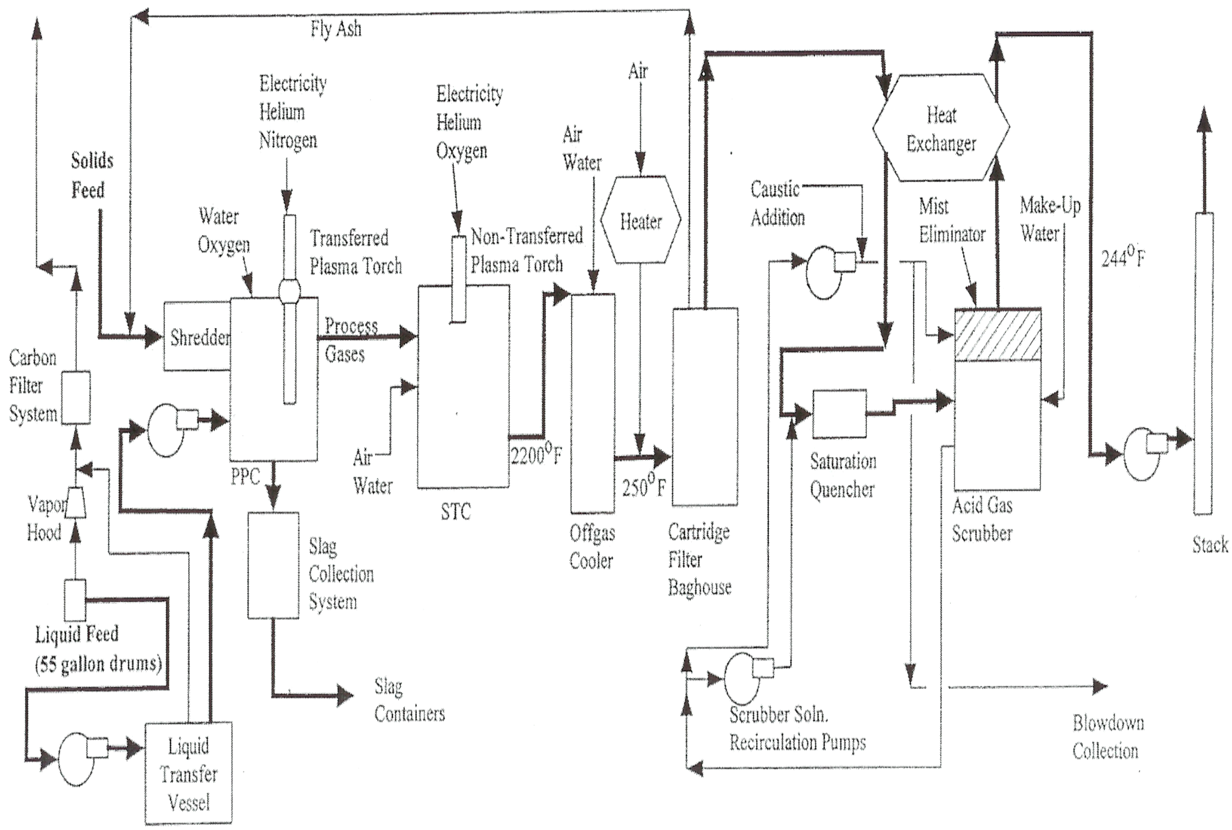

Figure 3. Flow Diagram for the PAHWTS.

Once in the PPC, the waste is heated to temperatures exceeding 980°C (1,800°F) by a transferred arc plasma torch. Subjected to the heat of the plasma arc, most metals and other inorganic materials are reduced to molten slag. Approximately half of the heavy metals (e.g., lead) fed into the PPC are expected to vaporize and end up in the gas/particulate scrubber system. Water and organics in the feed are volatilized, as are most chlorides and sulfates. The organics are partially oxidized in the PPC, and the offgas is maintained at approximately a 45% $CO2/(CO+CO2)$ ratio. The PPC is refractory-lined, double-walled, and water-jacketed. The rotating centrifuge is refractory-lined and externally cooled by a water spray. Brush contacts are provided between the centrifuge and PPC to conduct electric current from the transferred plasma torch in the PPC back to the power supply. A surge relief system, which includes a surge tank, provides protection in the event of an overpressure situation in the PPC.

The slag collection chamber is equipped with safety and slag molds, and their position can be determined remotely. While processing waste, the safety mold is lifted up against the PPC. The two main functions of the safety mold are to act as a heat barrier between the slag collection chamber and the PPC and to contain any unprocessed waste that may escape the PPC prior to complete processing. The function of the slag mold is to contain processed slag from the PPC during the slag-pour stage.

When the centrifuge is full of slag, feeding is interrupted, and the conditioning stage begins. Conditioning is accomplished by holding the molten mass at temperature for a specified period of time in order to drive off virtually all of the volatile components. This stage ensures that all solids are melted and all organics in the region are volatilized and transferred to the STC before the safety mold is removed and pouring is initiated. The main control factor for the conditioning stage is residence time, which is determined by the size and type of feed material. (Larger pieces of material require longer conditioning times to ensure that the solids have been fully melted and that volatilization is complete.)

The slag/pour stage, a semi-automatic process, immediately follows conditioning. First, the safety mold is removed and the slag mold put in place. The capacity of the slag mold is less than the volume of a full centrifuge; therefore, only part of the molten slag can be poured at this time. The rest of the molten slag remains inside the centrifuge in order to enhance the next batch of waste processing. When the slag mold is in place, the centrifuge is decelerated, causing the slag to pour out the central opening and into the mold. A spot infrared thermocouple signals the control console when the mold is full and pouring is to be terminated. Once pouring is complete, the centrifuge is returned to full speed, the safety mold is replaced, and waste feeding is resumed.

The offgas from the PPC flows through an offgas port to the secondary treatment chamber (STC). During reducing conditions, this offgas is rich in carbon monoxide and hydrogen, and is flammable. The STC is designed to fully oxidize these combustible species and provide a 2-second residence time for the products of combustion at temperatures above 980°C (1,800°F). Air is added to complete the reaction and raise the exit oxygen level to more than 5%. If necessary, supplementary heat is added to the system by a nontransferred plasma arc torch to maintain the temperature inside the STC in the range of 980°C to 1,315°C (1,800°F to 2,400°F). The STC is sized to handle the maximum gas load that can result from processing the highest organic feed at the maximum feed rate through the PPC.

The STC is a double-walled, water-jacketed, refractory-lined vessel. The overall configuration allows the STC's internal temperature to be maintained at 980°C to 1,315°C (1,800°F to 2,400°F). The STC offgas temperature is monitored by a thermocouple and controlled by the STC nontransferred arc plasma torch heater and a water injection system to ensure that temperatures are maintained within limits. The inside volume of the STC is approximately 285 cubic feet (8 cubic meters) and ensures a minimum 2-second residence time when running at the maximum flow rate.

The gas/particulate scrubber system is an offgas treatment system that further processes the gas exiting the STC. This system ensures that all emissions from the PAHWTS are within the applicable regulatory limits and controls the levels of particulates, metal vapors, HCl, and SOx, while preventing the formation of other products such as dioxins and furans that could be harmful to public health and the environment.

In the offgas cooler, tempering water added to the hot gas coming from the STC provides for removal of an estimated 90% of the input mercury from the gas stream. This mercury is pumped from the primary mercury trap to the secondary mercury trap in the absorber sump, where it, along with the remaining estimated 10% of the input mercury removed by the offgas scrubber, is subsequently pumped to packaging for disposal.

Particulates remaining entrained in the offgas are removed from the system in the dry, primary, cleanable cartridge filters. Particulates can be collected in 1- or 5-gallon containers for rapid, safe removal from the system. These containers can subsequently be fed back into the PPC.

The HCl in the gas stream is contacted with NaOH solution and converted to salt in the saturation quencher (approximately 90%) or the absorber sump (the remaining 10%). Wastewater is blown down to maintain salt concentrations well below crystallization. Blowdown is treated in a wastewater treatment plant or disposed of off-site as a HW.

The gas/particulate scrubber system incorporates an induced draft blower located upstream of the stack. It is designed to maintain a negative pressure of approximately 50 millibars at the outlet of the STC. Internal components in the fan are resistant to chloride salt corrosion, and the fan is controlled in such a way that changes in the PPC gas generation have minimal effect on the pressure in the STC. The fan is controlled by suction throttling to maintain constant pressure in the PPC.

Figure 4 is a schematic of the solid and liquid feed system. The solids feed system consists of a shredder with a lock chamber feed system, a bulk solids chute for the introduction of bulk waste, and a screw feeder which meters bulk and/or shredded solids into the PPC. Solids up to the size of 5-gallon (19-liter) pails are processed through the shredder and directed into the screw feeder, while bulk solids are dumped, through a chute, directly into the screw feeder. The screw feeder subsequently conveys both waste types into the PPC; the solids feed rate is controlled through adjustments to the screw feeder RPM. The waste to be shredded is manually fed from a gravity conveyor into the nitrogen-purged lock chamber located above the shredder at a rate defined by the control computer. The lock chamber prevents the transfer of gases from both the PPC and solids feed system to the atmosphere, and consists of two automatic isolation gates which are actuated locally by the operator. The isolation gates are interlocked so they cannot be opened at the same time. This solids feed system is purged with nitrogen to mitigate the possibility of ignition of flammable materials. There is a continuous purge to keep the chamber free of combustible gas buildup. There is also a higher flow nitrogen purge to flush the chamber of high oxygen after one of the gates has opened. There is an interlock that will prohibit the opening of a gate unless the system has been high flow purged with nitrogen for approximately 20 seconds.

The liquid waste feed system consists of a drum emptying station, a liquid transfer vessel, and a liquid waste feed pump. The 55-gallon (208-liter) drums are placed in an enclosure (i.e., the drum emptying station) by the operator, and the pneumatic drum pump suction wand and/or the pump/agitator are inserted. The contents of the drums are pumped into the liquid transfer vessel via either the pneumatic drum pump or inserted drum pump/agitator; both pumps are physically configured with hoses, and the one used is determined by the hose connections between the drum and transfer line. Each of the pumps is operated by a hand/off switch that actuates an air solenoid valve through the PLC. The solenoid valves introduce air to the air motors operating the pumps. The liquid transfer vessel is agitated and is serviced by a progressive cavity pump feeding the PPC. The agitator

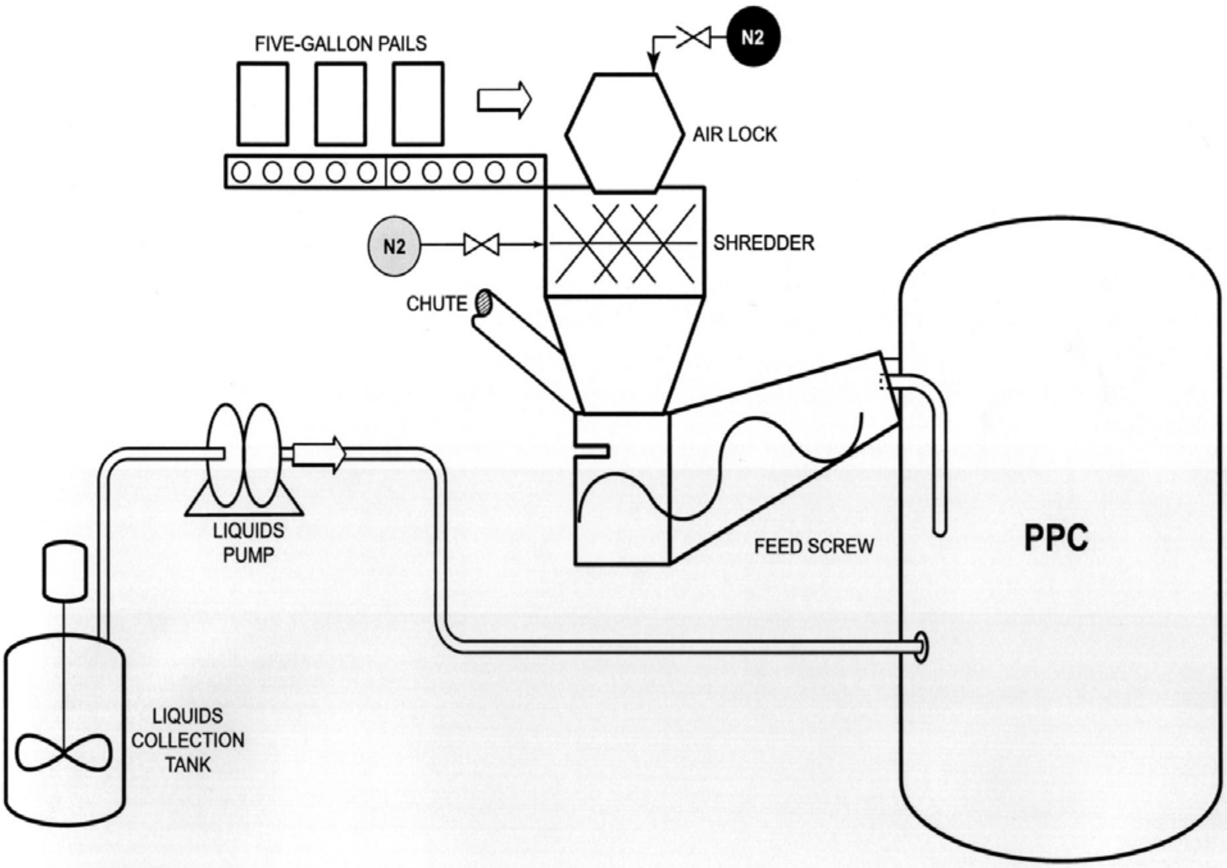

Figure 4. Schematic of the Liquid and Solid Feed System. [Note that the 55-gallon (208-liter) drum enclosure is not shown.]

is turned on manually by the operator via a hand switch; when the agitator is in the AUTO mode, it turns off when the level in the tank falls to 10% full and turns on when the level rises to 15% full. The tank is monitored by a level transmitter reporting to a programmable logic controller (PLC).

The liquid transfer vessel and the hood over the drum emptying station are vented to a carbon canister organic vapor adsorption system to control organic vapor emission. The blower that draws the vent gases is operated via a hand switch.

Feed of liquid and solids to the PPC is continuous, not batch-wise, and is controlled by an operator who sets the ratios of both liquid waste and solid waste and sets the overall waste feed rate in the control computer. Alternatively, the operator can set the individual solid and liquid rates independently or allow the liquid feed rate to vary with the level in the liquid transfer vessel. These set-points are established based on the reaction parameter (e.g., temperature, oxygen, stack emissions) target levels required to maintain stable operating conditions. Waste feed may not be initiated unless the temperature in the PPC is above 980°C (1800°F). During operation, the waste feed rate will be automatically ramped downward or stopped if there is a low temperature in the PPC.

The flow rate of the liquid wastes is maintained by a flow controller, in conjunction with a mass flow meter, which adjusts the RPM of the variable speed motor on the progressive cavity pump, as necessary. Zero flow indication on the flow meter when the pump is on indicates that there is a pump malfunction, an empty tank, a line blockage, or another similar situation. As a result, a zero

flow indication initiates a low flow alarm, which also turns off the pump and directs the PPC inlet valve to open (i.e., opens it to nitrogen supply and closes it to liquid waste supply).

The controls for starting and operating the solids feed system were provided by the manufacturer of the shredder/auger system. These controls tie into the main PLC for the PAHWTS and the cooling water and nitrogen instruments supplied by Retech which constitute a portion of the solid waste feed system.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Over the past 15 years, there have been numerous projects using either laboratory-scale or prototype plasma arc systems that have demonstrated the efficacy of thermal plasmas in destroying many types of waste materials (either simulated or actual). In general, inorganic materials are melted and rendered into a dense, obsidian-like material called slag, which will pass EPA leach tests, and organic material is vaporized and chemically converted into benign gases that can be emitted into the atmosphere. In 1995 and 1996, Retech, the company that built the Norfolk PAHWTS, conducted treatability studies on actual waste materials provided by several DoD facilities. They used a plasma arc system similar in design to the PAHWTS but considerably smaller, so the processing rates were significantly lower than those for the PAHWTS. The wastes included electroplating sludge and paint blast media from an Army repair depot, ash from an Army medical incinerator, and paint from NSN. In every case, emissions from the plasma arc system met regulatory requirements and the slag passed the EPA leach test.

There have also been many production-scale plasma arc systems that are in operation or in various stages of assembly or testing. Descriptions of these have been documented in a recent report issued by NRL [8]. The following are brief synopses of several of these projects.

- The Defense Logistics Agency contracted with a company to install a transportable production plasma arc system at their Port Clinton, Ohio, asbestos storage facility. It has been used to destroy several tons of asbestos.

- The Army has contracted with a company to design, construct, and test a plasma arc system for the destruction of completely assembled smoke and pyrotechnic ordnance. The system has been successfully tested at the contractor's site, permits have been obtained, and it is currently being installed at the Hawthorne Army Depot.

- The Army has contracted with another company to design, construct, and test a transportable system for the destruction of medical waste. The system has been installed in an industrial park in northern Virginia and has been used to treat 20 tons of actual medical waste.

- Retech built and delivered a plasma arc system in Muttenz, Switzerland, which has been used to process pharmaceutical sludges in 200-liter drums.

- Retech built and delivered a system in Muenster, Germany designed to process products from washing soils contaminated by military explosives and chemical warfare agents and is currently undergoing qualification trials.

It is, therefore, clear that plasma arc is a well-developed technology for the treatment of various types of wastes, but it has not yet progressed to the point of what might be considered for full commercialization. This is best evidenced by the fact that most of the customers for plasma arc systems have been government organizations.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

There are several advantages in using plasma arc systems for the treatment of waste materials over conventional fuel-fired incinerators. The first is obviously the higher temperatures and higher energy fluxes of the plasma. The maximum heat flux for an oxygen-fuel flame is approximately 0.3 kW/cm^2 whereas the energy flux for a direct-current transferred arc is approximately 16 kW/cm^2. The higher flux for plasma arc devices is due to the higher temperatures, the higher gas velocities at the nozzle of the torch, and higher thermal conductivities of the plasma gases. For transferred arcs there is the additional heat flux from the electron transfer in the area of the anode arc root attachment in the material being treated. The second advantage is that the total gas volume required to sustain a plasma arc is considerably less than that required for a fuel-fired burner. It has been estimated that for a given throughput of material, the total gas volume required for a plasma arc system is only 10% of that for a fuel-fired burner system. This means that the off-gas handling system can be significantly smaller for a plasma arc system. A third advantage is that the plasma energy can be provided to a system with independent control of the oxygen concentration (i.e., oxidizing, reducing, or inert gas environments, independent of the reactor temperature). This is a distinct advantage over combustion systems where the available energy flux and the oxygen concentration are not independent of the temperature. Also, it is possible to operate with high-energy fluxes with highly reducing systems or highly inert systems, although certainly the cost of the gases used will be a factor in making such decisions.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The performance objectives were to operate the PAHWTS at Naval Station Norfolk under a Resource Conservation and Recovery Act (RCRA) Research, Development and Demonstration (RD&D) permit for approximately 18 months for the ESTCP demonstration to be followed by operation under a RCRA Part B permit in full production while achieving compliance with 40 CFR Part 63 and the 1990 Clean Air Act Amendments. Under the RD&D permit, the system would have been limited to treating 881 lb/hour (400 kg/hour) and 33,000 lb/month (15,000 kg/month). In full production, the system would have been capable of treating between 1.5 and 2.5 million lb (0.7 to 1.1 million kg) per year, depending on whether it was operated on a 5-day-per-week or 7-day-per-week schedule.

3.2 SELECTION OF TEST FACILITY

In the mid-1990s, NSN began to explore the feasibility of using alternative methods to dispose of its HW to reduce costs and limit federal liability for the waste when it left the installation. At the same time, the NRL was conducting investigations into the application of thermal plasma technology for the destruction of simulated Navy shipboard waste. Thermal plasma technology (involving the generation of sustained plasma arcs) had been extensively developed in the 1950s and 1960s first as a source of high-temperature gas to test heat shields on spacecraft reentry vehicles and then in the metals processing industry for ore reduction, scrap metal recovery, and high temperature alloying. It was recognized in the early 1980s that with some modifications thermal plasma technology could be applied to the safe processing of various types of HWs. Several projects were executed and pilot-scale plasma arc waste treatment systems were built in the late 1980s and early 1990s, generally demonstrating the efficacy of the technology for waste destruction. It was partly as a result of the success of these earlier studies that the Navy decided to investigate plasma arc technology for destruction of waste onboard Navy ships. NRL, sponsored by the Office of Naval Research Environmentally Sound Ships Program, acquired a plasma arc system in 1994 and initiated studies on destruction of cellulose and organic liquids.

In 1995, discussions were held between NSN and NRL concerning the possible application of plasma arc technology for the destruction of the HW generated at the naval base. These led to an agreement to jointly sponsor a proposal to ESTCP to demonstrate and validate plasma arc technology as a viable method for treating HW generated at the base. This proposal was accepted and the project approved in the summer of 1995.

The intent of the joint NSN/NRL project was to establish a demonstration PAHWTS at the naval base to demonstrate complete destruction of solid and liquid HWs on a production basis and to obtain operational data needed to document the performance and cost-effectiveness of plasma arc technology. It was anticipated that establishment of the PAHWTS at NSN would provide the following benefits.

- Economy of operation — The PAHWTS operation would be more economical than disposing of the HW through conventional channels with ultimate disposal in a landfill or incinerator.

- Significant reduction in the volume of waste material requiring disposal.

- Decomposition and oxidation of organic materials leading to emission of only carbon dioxide and water vapor.

- For inorganic materials, production of a residue consisting of a glass-like, nonleachable substance (slag) that is easy and safe to handle, transport, and dispose of.

- Minimization of the handling and transport of HW at the naval base, thereby reducing potential worker and community exposure to these wastes.

- Minimization of long-term federal liability for disposal of HW off-site.

In May 1996, NRL issued a request for proposals (RFP) for design, construction, and testing of a PAHWTS. The statement of work for the RFP consisted of a combination of component and performance specifications that would produce a system to meet all regulatory requirements while being capable of destroying most of the HW generated at the NSN when operated on a continuous basis. In September 1996, NRL awarded a contract to Retech Services, Inc., at the time a division of Lockheed Martin Company, for development of the PAHWTS. Details of the requirements for the system are provided in the next section. The contract also required the successful execution of a factory inspection test (FIT) that required the introduction of specific materials into the system at the minimum specified feed rates and the demonstration of the destruction of the materials, with the emissions meeting all regulatory requirements.

3.3 TEST FACILITY CHARACTERISTICS

3.3.1 Naval Station Norfolk, Virginia

NSN is located in the northern portion of Norfolk, Virginia, and is the world's largest naval base and home of the Atlantic Fleet. The base comprises more than 4,600 acres (18 sq km), contains more than 3,000 facilities, and is home to more than 84,000 military and civilian personnel. Activities at the installation generate approximately 2.5 million lb (1.1 million kg) of hazardous and nonhazardous industrial waste annually. Table 1 shows the principal types of waste that are generated, more than half of which come from ships at the base. The costs of disposing of this waste are significant. On-site accumulation and packaging, and off-site transfer and landfill disposal by private firms under contract to the Navy (via the Defense Reutilization Marketing Office) are well over \$3 million annually and average \$1.50 per lb (\$3.30 per kg).

Table 1. Types of Hazardous and Industrial Waste Generated at Naval Station Norfolk.

Paint (including latex, lead-based, and metal-oxide-containing)
Solvents, both halogenated and nonhalogenated
Cloth rags contaminated with oil, hydraulic fluid, and solvents
Dirt contaminated with oil and hydraulic fluids
Oil and lubricating oil
Tubes of grease
Reactive chemicals
Plastic media blast material contaminated with paint
Batteries containing acids and heavy metals
Adhesives
Petroleum distillates
Sludge from high-pressure-water paint removal operations

3.3.2 Retech Test Facility, Ukiah, California

Retech Services LLC in Ukiah, approximately 100 miles north of San Francisco, employs approximately 225 people — 55% of whom work in manufacturing, 35% in engineering, and 10% in sales and administration. Their facility was established in 1975 and consists of several buildings with more than 140,000 square feet (13,000 square meters) of manufacturing space. In the early years of operation, Retech's principal business was manufacturing equipment for melting reactive metals such as titanium and zirconium. Electric energy was used as the heating method and included consumable electrode arcs, plasma, electron beam, and induction heating. Currently, Retech's primary business is manufacturing aerospace alloy melting equipment.

Retech conducted their first studies related to treatment of various types of waste in 1985 using a fixed hearth plasma arc system. They later developed the PACT system with a rotating centrifuge in the PPC, with the system designation based on the diameter of the centrifuge in feet (e.g., a PACT-5 system would have a 5-foot-diameter centrifuge). Retech began evaluating PACT systems on simulated waste streams in 1987 and in 1991 constructed a PACT-6 for EPA to use for demonstrations and testing. It is now in Butte, Montana, operated by the Department of Energy. The first PACT-8 system was built for Moser-Glaser Company in Switzerland and is currently used for processing HW.

The PAHWTS was constructed by Retech in their high-bay manufacturing and testing building. It has a ceiling height of 65 feet (20 meters), an overhead 20-ton bridge crane, and sufficient electrical power to operate multiple plasma arc systems. The construction and testing of the system were authorized under Permit Number 2080-3-14-98-77-12 issued by the County of Mendocino (California) Air Quality Management District. Materials processed in the PAHWTS were limited to Mendocino County soil, vegetable oil, latex and epoxy paint, oil-soaked rags, and methanol mixed with trichloroethane. The permit did not authorize the treatment of HW, so these materials (other than the soil) had to be purchased and delivered to Retech.

3.3.3 PAHWTS Specifications

The requirements developed by NRL for the PAHWTS were a combination of component and performance specifications. The following components had to be provided by the contractor: feeder systems, a primary processing chamber containing a plasma torch, a slag collection chamber and extraction mechanism, a secondary treatment chamber containing a plasma torch, an offgas treatment system, and a control and data acquisition system. The types of waste capable of being processed by the PAHWTS are those listed in Table 1. The PAHWTS had to be capable of continuous 24-hour-per-day operation, with the average percentage of down time (defined as the time when waste material was not being introduced into the system and destroyed) for procedures such as slag extraction and the performance of preventive and corrective maintenance not exceeding 40%. The average processing rate for the wastes listed in Table 1 was specified to be not less than 600 lb (273 kg) per hour for inorganic materials and not less than 450 lb (205 kg) per hour for organic materials, with the processing rate for mixtures of inorganic and organic materials interpolated between those two values. These throughputs were selected to enable the PAHWTS to process more than 80% of the total waste generated at the base if operated continuously with an uptime of 60%.

There were several requirements for feeding this waste into the PAHWTS. Since many of the waste liquids are contained in 55-gallon (208-liter) drums, the PAHWTS had to be capable of tapping and pumping the liquids from the drums directly into the primary processing chamber, with a provision that operators would not be exposed to the contents or vapors emanating from the contents of the drums. Much of the waste is in 5 gallon (19 liter) metal containers or smaller. For these, the feeder required a mechanism capable of shredding the containers and their solid contents, then introducing the shredded material continuously into the primary processing chamber.

The emissions from the PAHWTS during treatment of any of the materials listed in Table 1 could consist only of particulate-free gases and a vitrified solid slag. The PAHWTS had to comply with 40 CFR Part 63 (National Emission Standards for Hazardous Air Pollutants), 40 CFR Part 50 (National Primary and Secondary Ambient Air Quality Standards), 40 CFR Part 60 (Standards of Performance for New Stationary Sources), and 40 CFR Part 264 (EPA Regulations for Owners and Operators of Permitted Hazardous Waste Facilities — Subpart O). Since the PAHWTS was to be located in Virginia, it had to comply with the Virginia Department of Waste Management Regulation VR 672-10-1 (Hazardous Waste Management Regulations) and Virginia Regulations for the Control and Abatement of Air Pollution VR 120-01. Any slag generated by the PAHWTS had to be capable of passing the EPA TCLP test for all TCLP materials.

In accordance with EPA standard 40 CFR Part 63 and the 1990 Clean Air Act Amendments, the pollutants emitted by the PAHWTS into the atmosphere had to be limited to levels reflecting the application of the Maximum Achievable Control Technology, designated as the MACT standards, summarized in Table 2. In addition to meeting these standards, the emissions of NOx during the treatment of any of the materials listed in Table 1 could not exceed 1,000 parts-per- million.

Table 2. MACT Standards for PAHWTS.

Dioxins and Furans	0.20 nanograms TEQ/dscm
Particulate Matter	34 milligrams/dscm
Mercury	45 micrograms/dscm
Semi-Volatile Metals (Cd and Pb, combined)	24 micrograms/dscm
Low-Volatile Metals (As, Be and Cr, combined)	97 micrograms/dscm
Hydrogen Chloride and Chlorine	21 ppmv
Carbon Monoxide	100 ppmv
Hydrocarbons (expressed as propane)	10 ppmv
Minimum DRE for each POHC	99.99%

Notes:
TEQ = toxicity equivalency of 2,3,7,8 tetra-chlorinated dibenzo-p-dioxin; dscm = dry standard cubic meter; ppmv = parts per million by volume; DRE = destruction and removal efficiency; POHC = principal organic hazardous constituent; all values must be corrected to 7 percent oxygen; standards require meeting CO or hydrocarbon limits, not both.

Other system requirements included the following.

1. The plasma torch in the primary processing chamber had to be capable of continuous operation at a power level of at least 500 kW for 200 hours without requiring replacement of any internal components such as electrodes. The exterior surface of the PPC could not exceed 50°C (120°F) during operation.

2. For protection against overpressure in the primary processing chamber, a surge tank had to be provided.

3. The slag collection chamber had to have a safety mold to collect slag that inadvertently escaped from the primary chamber during operation.

4. The secondary treatment chamber had to be designed such that all gases entering it from the primary chamber would be exposed to a temperature of at least 980°C (1800°F) for at least two seconds.

5. The heat source in the secondary treatment chamber had to be a plasma torch or resistive heating elements; it could not contain a fuel-fired burner.

3.3.4 Description of Factory Inspection Test (FIT)

The purpose of the FIT was to demonstrate that the PAHWTS had the capability to meet the required specifications indicated above, including minimum feed rate requirements, gaseous emissions, and slag leachability. Secondary objectives for the FIT included verification of satisfactory operation of system instrumentation and controls, and verification of satisfactory operation of the system program, sequences, alarms, and interlocks. It was anticipated that if the FIT were completed successfully, the data generated from the testing would facilitate permitting the PAHWTS at NSN. Although there are many different types of wastes generated at the base, as indicated in Table 1, it

was decided that the FIT should be conducted on four different materials representing a wide variety of solid and liquid organic and inorganic materials. These were Mendocino County soil (i.e., soil adjacent to the Retech facility), paint, rags soaked in diesel fuel and motor oil, and methanol mixed with trichloroethane.

Before initiating the formal FIT, Retech conducted several feed campaigns to ensure acceptable performance of the system. They included introducing soil and vegetable oil into the system to establish a slag base in the centrifuge and to verify operation of the STC and offgas treatment system.
The following are exact descriptions of the feed materials that were planned for the FIT.

- *Paint #1.* Devoe Coating Company epoxy coating kit, gray #861F2904, formula 151 type 4, component A, including steel containers

- *Paint #2.* Sherwin-Williams interior latex semigloss, white, B31 W041, including steel containers

- *Fuel.* Chevron diesel fuel #1

- *Oil.* Peak 10W30 automotive engine oil

- *Rags.* Aramark common shop rags (including multicolored scrap towels and clean used rags)

- *Containers for rags.* Tin-plated steel cans, galvanized steel cans, stainless steel cans, of size 13.2 to 17.0 liters (3.5 to 4.5 gallons)

- *Methanol/trichloroethane (TCA).* Standard industrial grade methanol and (1,1,1) trichloroethane in a ratio of 3.5:1

Table 3 provides results of an analysis of trace metals present in Mendocino County soil.

Table 3. Trace Metals Present in Mendocino County Soil.

Barium	12.0 mg/l
Chromium	0.4 mg/l
Cobalt	1.0 mg/l
Copper	0.4 mg/l
Nickel	1.2 mg/l
Zinc	2.3 mg/l

The following elements were not detected: antimony, arsenic, beryllium cadmium lead, mercury, molybdenum, selenium, silver, thallium, and vanadium.

3.4 PHYSICAL SET-UP AND OPERATION

Most of the FIT was conducted at Retech in October 1999 and consisted of seven separate runs. The only material not treated was oily rags because of a problem with the solids feeder, as discussed below. The solids feeder was repaired, and run #8 was conducted on the oily rags in March 2000. Table 4 is a summary of the different runs, including the feed material, the duration of the run, and the average feed rate for solid and liquid material. Also included is the total chlorine feed rate, which represented a portion of the methanol/TCA liquid feed.

Table 4. Summary of Treatment Runs Conducted during the FIT.

Run	Duration	Material	Average Feed Rate, kg/hr (lb/hr)		
			Solid	Liquid	CI*
1	3 hr	Dirt	180 (400)	0	0
2	2 hr	Dirt	180 (400)	0	0
3	3 hr	Gray epoxy paint**	22 (50)	191 (425)	0
5	3 hr	Methanol/TCA	0	200 (443)	53 (118)
6	2 hr	Methanol/TCA	0	153 (340)	54 (120)
7	2 hr	White latex paint	0	191 (425)	0
8	4 hr	Oily rags	91 (200)	0	0

*Total chlorine as portion of liquid feed
**Includes paint cans

For the two dirt runs, the dirt was placed in 55-gallon drums and raised to the feeder platform using an overhead crane, then transferred to cardboard containers with a volume of approximately 5 gallons. The dirt-filled containers were placed onto the conveyor and introduced into the shredder at a rate of approximately one every 15 minutes. During feeding, the dirt piled up somewhat at the end of the auger, resulting in clumps of dirt falling into the centrifuge instead of in a continuous stream. On several occasions, the clumps of dirt extinguished the plasma arc, but the torch restarted quickly with no problems. It is believed that with proper adjustment of the auger speed and torch position, these torch outages can be minimized in the future operation of the system.

For the gray epoxy paint run, most of the liquid paint was poured into 55-gallon drums from which it was pumped into the liquids collection tank and then into the PPC. The empty 1-gallon paint cans were lifted on skids to the solids feeder platform. Four cans at a time were placed into cardboard boxes and introduced into the shredder at a rate of approximately one box every 8 minutes (equivalent to the 22 kg/hr rate indicated in Table 4). At the conclusion of this run, a problem developed with a valve at the interface between the auger and PPC. It was determined that this valve could not be repaired in a reasonable period of time, so it was decided that the FIT would be continued using only liquid materials. As a result, it was not possible to conduct the test on oily rags.

Run 4 was initiated using the white latex paint, but after approximately 45 minutes, the liquid feed line between the liquids collection tank and the PPC clogged, and the run was stopped. After the feed line was cleared, it was decided to abort run 4 and conduct the two methanol/ TCA runs before returning to the white latex paint. Methanol and TCA were pumped into the liquids collection tank

from 208-liter drums in the appropriate ratio, and they were mixed using an internal agitator prior to being pumped into the PPC.

The final run in October 1999 consisted of pouring the white latex paint into 208-liter drums, pumping the paint into the liquids collection tank, and then pumping it into the PPC for processing.

For run #8 in March 2000, the rags were initially soaked in the 10W30 engine oil, then placed in cardboard boxes. The approximate weight of each box was 11.4 kg (25 lb), and the plan was to feed them into the shredder at a rate of one box every 3.5 minutes, providing a feed rate of 205 kg/hr (450 lb/hr). Due to the relatively light weight of the containers and the smooth surface of the boxes, it took longer than the anticipated 3.5 minutes to process each container through the shredder and into the auger system. The boxes tended to ride on top of the shredder blades until the blades were able to catch the corner of the box, or until the next box pushed the first into the blades. The test continued at a feed rate of approximately one box every 9 minutes until a box bridged the blades and could not be moved. The rotational direction of the blades was changed in an attempt to shift the box, but that was unproductive. Another box was added in the hopes it would shift the first box, but this too was unproductive. The second box was prevented from fully entering the shredder chamber, and the airlock door could not be closed. To remove the boxes, the system had to be shut down and allowed to cool to gain access to the airlock.

After the boxes were removed and the PAHWTS brought back up to operating temperature, the test was resumed. This time, steel pails were substituted for the cardboard boxes. Two loaded pails contained one unit weighing 11.4 kg (25 lb). These were fed into the shredder at a rate of one unit every 3.5 minutes. Again there was a problem of the pails riding on top of the shredder blades but it was not as significant as with the cardboard boxes. The average feed rate was about one unit every 7 minutes, equivalent to about 91 kg/hr (200 lb/hr).

During all runs, the temperature in the PPC was 980° to 1,200°C (1,800° to 2,200°F), and the temperature in the STC was 980° to 1,100°C (1,800° to 2,000°F). The primary plasma torch was always operated in the transferred mode while material was being introduced into the PPC. Once the STC was at operating temperature for the processing of organic materials, it was possible to turn off the secondary torch as the combustion process provided sufficient energy to maintain the chamber at the required operating temperature.

At the completion run #7, the slag mold was put into position below the PPC and the rotation of the centrifuge slowed, allowing the molten slag to pour into the mold. Approximately half the contents of the centrifuge was poured into the mold, then extracted from the system and allowed to cool.

3.5 SAMPLING/MONITORING PROCEDURES FOR ANALYTICAL METHODS

During the October 1999 FIT, stack emissions were monitored by personnel from the U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM) using EPA-approved reference methods, which are described below. Due to funding and scheduling constraints, it was not possible to have USACHPPM monitor the emissions during the March 2000 test on oily rags. Table 5 provides a summary of the different emissions tests conducted for each feed material.

Table 5. Summary of Sampling Methods for Measuring Stack Emissions.

Feed	Sample	Collection Frequency	Sampling Method	Analysis Parameters
Dirt	Exhaust Gas	Continuous Continuous Continuous Continuous Continuous	RM 5 RM 29 RM 2 RM 4 RM 3	PM Cd, Pb, Hg Stack gas volumetric flow rate Moisture Combustion gases CO_2 O_2 (Orsat)
Paint	Exhaust Gas	Continuous Continuous Continuous Continuous Continuous	RM 26A RM 29 Method 0023A RM 2 RM 4 RM 3	PM/HCI/Cl2 Cd, Pb, Hg CDD/CDF Stack gas volumetric flow rate Moisture Combustion gases CO2 O2 (Orsat)
TCA/Methanol	Exhaust Gas	Continuous Continuous Continuous Continuous Continuous	RM 26A RM 29 Method 0023A Method 0040 RM 2 RM 4 RM 3	PM/HCI/Cl2 Cd, Pb, Hg CDD/CDF TCA Stack gas volumetric flow rate Moisture Combustion gases CO_2 O_2 (Orsat)

PM = particular matter
CDD/CDF = dioxin/furan

In addition to the emissions measurements conducted by USACHPPM, during all feed campaigns (including run #8 in March 2000), the following species were monitored in real-time using continuous emissions monitors: total hydrocarbons, CO, and NOx. The following components constituted the continuous emissions monitoring suite.

- *Perma Pure Inc.* GASS-II Sample conditioning system

- *Thermo Environmental Inc.* Model 51 Total Hydrocarbon Analyzer

- *Thermo Environmental Inc.* Model 48C Gas Filter Correlation Carbon Monoxide Analyzer

- *Thermo Environmental Inc.* Model 42C High Level Chemiluminescence NO-NO2-NOx Analyzer

The instruments have analog outputs that are interfaced to a National Instruments Model 6B analog-digital data collection system. During the FIT, the data were collected and recorded approximately once per second by the central PAHWTS data acquisition system.

The Perma Pure Inc. GASS-II sample conditioning system is a Nafion-based stack monitoring sample conditioning system. The GASS-II heats and dries samples to a dew point of -25°C at a flow rate of 25 standard liters per minute.

The Thermo-Environmental Inc. Model 51 total hydrocarbon analyzer uses a flame ionization detector that is capable of detecting most hydrocarbons. The analyzer can heat all components that

come in contact with the exhaust gas to at least 200°C to prevent condensation. It has internal calibration and can be set for continual periodic calibration. The detection range is 0.1 to 10,000 parts-per-million (for propane).

The Thermo-Environmental Inc. Model 48C gas filter correlation carbon monoxide analyzer is a microprocessor-based nondispersive infrared analyzer. EPA designates it as a reference method for the measurement of ambient concentrations of carbon monoxide pursuant with the requirements defined in 40CFR53. The detection range is 0 to 10,000 parts-per-million.

The Thermo-Environmental Inc. Model 42C high-level NO-NO2-NOx analyzer is a microprocessor-based chemiluminescence instrument that can provide quantitative information on the various nitrogen oxides. The instrument is internally calibrated and uses zero grade air for the ozonator feed. The detection range is 0 to 10,000 parts-per-million.

In addition to the above emissions measurements, metals emissions were also monitored using the multimetals continuous emissions monitoring system (MMCEMS) developed under a separate ESTCP project by the Naval Air Warfare Center Weapons Division China Lake and Tank and Automotive Command-Armaments Research and Development Research Center (TACOM-ARDEC) at Picatinny Arsenal [9]. The MMCEMS had previously been validated on an Army munitions deactivation furnace, but it was decided to compare its results with those obtained by USACHPPM using EPA Method 29 on the PAHWTS because the moisture content in the stack would be much higher, complicating the metals emissions measurements.

During the FIT runs in October 1999, the MMCEMS continuously extracted stack gas using a shrouded probe mounted in the sampling port provided. The instrument trailer for the MMCEMS was positioned outside the building, immediately adjacent to the exhaust stack. A 6-meter (20-foot) heated sample line was used to connect the shrouded probe to the MMCEMS elemental analyzer. The instrument automatically executed sample introduction and plasma emission measurements once every 66 seconds. During each sample introduction cycle, the concentrations of all of the metals were measured simultaneously.

4.0 PERFORMANCE ASSESSMENT

In February 2000, USACHPPM issued their final report on the results of the stack emissions testing. This was a comprehensive report that included a narrative text, tables, and many appendices that described in detail the sampling equipment and procedures, sample analysis and recovery, calibration procedures, and data [10]. Only a brief summary can be included here.

Table 6 provides the average volumetric flow rates, the oxygen concentrations, and the moisture concentrations for the gases emitted from the stack for each run. It can be seen that water vapor constituted a considerable fraction of the emissions from the system, especially for the processing of organic material.

Table 6. Average Volumetric Flow Rates, Oxygen Concentration, and Moisture Concentration in the Stack during FIT (as measured by USACHPPM for each run).

Run	Material	AVFR dscm/hr (dscf/hr)	O_2 Concentration %	Average Moisture Concentration %
1	Dirt	2160 (76,300)	11	25
2	Dirt	2095 (74,000)	12	28
3	Gray epoxy paint	2200 (77,000)	12	41
5	Methanol/TCA	2223 (78,500)	11	38
6	Methanol/TCA	2078 (73,400)	11	32
7	White latex paint	2019	14	27

AVFR = average volumetric flow rate
dscm/hr = dry standard cubic meters per hour
dscf/hr = dry standard cubic feet per hour

Table 7 provides a summary of the average emissions for each run as measured by USACHPPM (corrected to 7% oxygen) or by the continuous emission monitors. The former includes high volatility metals (Hg), semivolatile metals (Pb and Cd), low volatility metals (As, Be, and Cr), particulate matter, HCl/Cl2, and dioxin/furan (expressed as TEQ, or toxicity equivalency of 2,3,7,8 tetra-chlorinated dibenzo-p-dioxin). The latter includes total hydrocarbons, CO, and NOx. Not included in the table is the destruction and removal efficiency (DRE) for the TCA for runs 5 and 6 as measured by USACHPPM. For run 5, the DRE was 99.99993%, and for run 6, it was 99.99991% indicating that the system was extremely efficient in destroying this compound. (Note that the regulatory standard minimum DRE is 99.99%).

The emissions from the PAHWTS were significantly below the regulatory limits for metals, particulate matter, and total hydrocarbons for all runs. The emissions of CO were well below the regulatory limit for all runs except for the gray epoxy paint and oily rags. The PAHWTS results were due to the fact that this was the first feed of primarily organic material, which required a significant amount of time to establish steady-state operating parameters, resulting in complete combustion in the STC.

Table 7. Summary of Emissions from Stack for Each Run during FIT (regulatory limit indicated in parentheses at the top of each column).

Run	Material	HVM (45)	SVM (24)	LVM (97)	RM (34)	HC1 (21)	TEQ (0.20)	THC (10)	CO (100)	NOx *
1	Dirt	6.8	0.8	1.3	3.6	-	-	3	50	500
2	Dirt	6.1	2.1	1.3	2.6	-	-	3	50	500
3	GEP	1.2	9.9	2.7	1.8	1.0	0.057	3	450	350
5	M/TCA	1.0	17.7	3.1	4.3	45.7	0.322	1	20	50
6	M/TCA	3.6	14.7	3.0	3.1	182.2	1.901	1	10	20
7	WLP	1.4	5.7	2.0	0.2	62.7	1.099	1	5	5
8	Oily Rags							1	265	490

GEP = gray epoxy paint (with cans)
M/TCA = methanol/TCA
WLP = white latex paint (without cans)
HVM = high volatile metals (Hg), expressed as micrograms/dscm
SVM = semivolatile metals (Pb and Cd), expressed as micrograms/dscm
LVM = low volatile metals (As, Be, and Cr) expressed as micrograms/dscm
PM = particulate matter, expressed as milligrams/dscm
TEQ = nanograms toxicity equivalency of 2,3,7,8 tetra-chlorinated dibenzo-p-dioxin/dscm
THC = total hydrocarbons, expressed as parts-per-million
CO = carbon monoxide, expressed as parts-per-million
NOx = combined total of NO and NO2, expressed as parts-per-million
*There is no regulatory limit for NOx; however, the contract specified a maximum of 1,000 parts-per-million

The establishment of optimum operating parameters was not final until the very end of the run. The CO results were most likely due to the length of time the system had been down and the inability to establish optimum operating parameters during the inconsistent feed of the metal pails containing the rags. The performance of the system after optimum steady-state combustion conditions were achieved is well illustrated by the low levels of CO and NOx during the methanol/TCA and white latex paint runs.

The HCl/Cl2 and dioxin/furan emissions from the system were below the regulatory limits for the dirt and gray epoxy paint runs. However, they exceeded the limits for both methanol/TCA and the white latex paint runs. For the runs that included TCA, the chlorine loading on the system was quite high, and it is believed that the high levels of HCl during the white latex paint run was most likely due to the presence of residual chlorides from the previous runs. An examination of the system subsequent to the FIT indicated that there may have been some leakage between the two sections of the heat exchanger (see Figure 3) through which gases passed before and after passing through the scrubber. Such a leakage would have allowed some HCl to bypass the scrubber and enter the stack. Since the elevated levels of dioxin/furan essentially tracked the elevated levels of HCl, it is reasonable to assume that there was a correlation and that if the HCl could be reduced, the dioxin/furan concentrations could be reduced as well. The leaks between the two sections of the heat exchanger were corrected after the completion of the FIT. Another action that could have been pursued to reduce dioxin/furan emissions was to better insulate the offgas cooler, to ensure that the offgas entering the cooler was more rapidly quenched and thus would spend minimal time in the temperature range for dioxin formation.

The comparative results for the measurements of metals emissions using the MMCEMS can be found in Reference 9.

5.0 COST ASSESSMENT

5.1 COST REPORTING

TAMS Consultants, Inc. performed several economic analyses on the use of the PAHWTS to destroy most of the HW generated at NSN. The most recent was in July 1999 [11] and took into account several scenarios related to possible reductions in the types and amounts of waste generated to ensure that the continued operation of the PAHWTS would be economically viable if pollution prevention efforts at NSN were successful in reducing the generation of HW.

First TAMS analyzed the costs associated with the existing procedure of contracting for the disposal of HW. Most data for this analysis was obtained in a memorandum from Gary Koerber of NSN in April 1999 [12]. The Defense Reutilization and Marketing Office (DRMO) incurred costs for reuse or recycling of waste; the Public Works Center (PWC) Norfolk incurred costs for removal of waste for ultimate disposal. The total amount of waste generated in fiscal year (FY) 1998 was 2,425,918 lb (1,103,000 kg). The total cost for disposal was \$3,505,570 in FY 1998, \$2,522,145 for PWC and \$983,425 for DRMO. This equates to an average cost of \$1.44 per lb (\$3.17 per kg).

Economic modeling for the PAHWTS was undertaken using the PC-ECONOPACK software developed by the Construction Engineering Research Laboratory [13] under sponsorship of the U.S. Army Corps of Engineers. The software calculates standardized life-cycle costs such as cumulative net present value, equivalent uniform annual cost, saving-to-investment ratio, and discounted payback period. The model requires basic economic parameters including project base year, discount rate, inflation rate, and project life. The base year for the economic analysis is 1998 and all inputs to the model were adjusted to 1998 dollars. Other major economic parameters used in the analysis were provided by the Navy and are as follows.

- Discount rate of 2.9%, applied to net annual costs, to develop present values
- Inflation rate of 2.1%, applied to all costs
- A required initial period of operation of the PAHWTS under an RD&D permit for 3 years, which limits the amount of waste that can be processed
- Full-scale operational life of 20 years beyond the RD&D period

Assumptions made with regard to operating parameters, operating capacity factor, and the feed rate of the PAHWTS will greatly affect the results of the economic analysis. Operating parameters define the duration and frequency of plasma torch warm-up periods, operating periods, actual treatment duration, utilities usage, and the length of the cool-down period. Utilities costs such as for electricity and gases will depend on the type of waste being treated. For this cost analysis, a composite waste stream consisting of paint, metal cans, oily rags, and chlorinated solvent in the ratio of their generation at NSN was assumed. The operational capacity factor is the percentage of the operating period the PAHWTS is actually treating waste. These variables are important to the overall cost of the project because they directly affect the yearly volume of waste the facility is able to treat, the volume of waste that will require off-site treatment, utility costs, labor costs, and the volume of slag generated. Because of the importance of the volume of slag generated and to better

model the long-term cost associated with the PAHWTS, the estimated feed rate and operational capacity factor were modeled for two scenarios — 5-day-per-week operation and continuous operation. The estimated feed rates were based on the design of the PAHWTS and ranged from 450 to 600 lb/hr (205 to 273 kg/hr). The weighted average feed rate of 525 lb/hr (239 kg/hr) was used in the economic analysis. An operational capacity factor of 60% was also assumed in the analysis.

For the 5-day-per-week operation, the facility would be staffed Monday morning through Saturday morning, with the system starting up on Monday each week and running around the clock until Saturday morning. Operating at an annual average capacity factor of 60% over the 94-hour weekly operation period would result in an average of 56.4 hours per week of actual treatment. Over a 1-year period, the total waste treated by the system would be approximately 1,540,000 lb (700,000 kg), leaving about 900,000 lb (409,000 kg) requiring off-site disposal.

In continuous operation, the PAHWTS would be operated 24 hours per day, 7 days per week. Applying the 60% operational capacity factor, actual treatment of waste would occur 5,256 hours per year, resulting in a total of 2,760,000 lb (1,254,000 kg) of waste being treated per year. Thus, under this scenario, the system would be capable of treating all HW generated at NSN.

The economic analysis took into account the following types of costs:

- Capital cost for PAHWTS
- Permitting costs
- Site and building modification costs
- Operation and maintenance costs, including labor, utilities (electricity and gases), supplies, stack emissions testing, equipment maintenance, and slag disposal

The capital cost for the system was estimated to be $6.9 million, with an additional $1.4 million for installation and permitting. Permitting costs included the development and submission of all applicable federal, state, and local permits. Site and building modification costs were estimated at $1.1 million. Thus, total initial costs were $9.4 million. Amortizing over 20 years resulted in an annual amortization cost of $470,000.

For labor, it was assumed that during each shift, there would be five full-time employees assigned to operation — two feed operators, two system operators, and one main operator. For 5-day-per-week operation, labor costs were $616,000 per year; for continuous operation, labor costs were $937,000 per year.

The costs for utilities and wastewater disposal were assumed to be:

- Electricity: $0.065 per kWh
- Nitrogen: $0.25 per 100 cubic feet ($0.09 per cubic meter)
- Oxygen: $0.25 per 100 cubic feet ($0.09 per cubic meter)
- Wastewater: $0.15 per gallon ($0.04 per liter)

It was assumed that annual costs for verifying stack emissions would be $100,000 and equipment maintenance costs, including replacing normal consumables, $200,000.

Costs to dispose of slag generated by the PAHWTS are greatly dependent on whether the slag can be disposed of as solid waste (delisted) or a HW (not delisted). The economic analysis considered both and applied a 1999 cost of $48 per ton for solid waste disposal and $1,440 per ton for HW disposal. It was not certain whether the slag could be delisted, so the following three scenarios were developed to better model the long-term effects of slag disposal cost on viability of the PAHWTS:

- Slag is delisted prior to unit startup and may be disposed of as a solid waste.
- Slag must be disposed of as a HW for 5 years, then as solid waste for the remainder of the life of the project.
- Slag must be disposed of as HW for the life of the project.

5.2 COST ANALYSIS

To account for potential initiatives undertaken at NSN that would result in lower quantities of HW requiring treatment, the following alternative operational scenarios were developed for the economic analysis.

- *Scenario 1 (Status Quo).* No implementation of the PAHWTS. HW quantities generated would be the same as in FY 1998 and would be collected by a licensed HW firm and delivered to off-site permitted HW processing facilities and/or landfills for all of the years of the economic analysis.
- *Scenario 2.* Quantity of all types of HW generated and requiring treatment would be 54% less than FY 1998 quantities in all years of operation of the PAHWTS, which would be operated on a 5-day-per-week schedule. With this level of reduction in the generation of HW, 5-day-per-week operation would be sufficient to treat all of the HW generated at NSN. Slag is not delisted. Scenario 2r is the same as Scenario 2 except the PAHWTS would be operated for enough hours each week to treat the quantities of waste generated.
- *Scenario 3.* Quantity of HW generated would be 27% less than FY 1998 quantities. This is a 5-day-per-week operation of PAHWTS, and slag is not delisted.
- *Scenario 4.* Due to pollution prevention efforts, the quantities of paint and contaminated rags are reduced by 50% from quantities generated in FY 1998. Quantities of all other types of HW would remain the same as in FY 1998. This is a 5-day-per-week operation, and slag is not delisted.
- *Scenario 5.* Same as Scenario 4, except slag is delisted in fifth year of operation.
- *Scenario 6.* Same as Scenario 4, except slag is delisted immediately.
- *Scenario 7.* Waste quantities would remain the same as in FY 1998 and the PAHWTS would operate continuously. Slag is delisted immediately. A variation of this is Scenario 7r where the PAHWTS would be operated only enough hours each week to treat the quantities of waste generated. Scenario 7r is the most favorable one for operation of the PAHWTS.

- *Scenario 8.* The pollution prevention program would eliminate all paint and rags waste. This is a 5-day-per-week operation, and slag is not delisted.
- *Scenario 9.* Same as Scenario 8, except slag is delisted in fifth year of operation.
- *Scenario 10.* Same as Scenario 8, except slag is delisted immediately.

Figures 5-8 present the results of the economic analyses for the 10 scenarios.

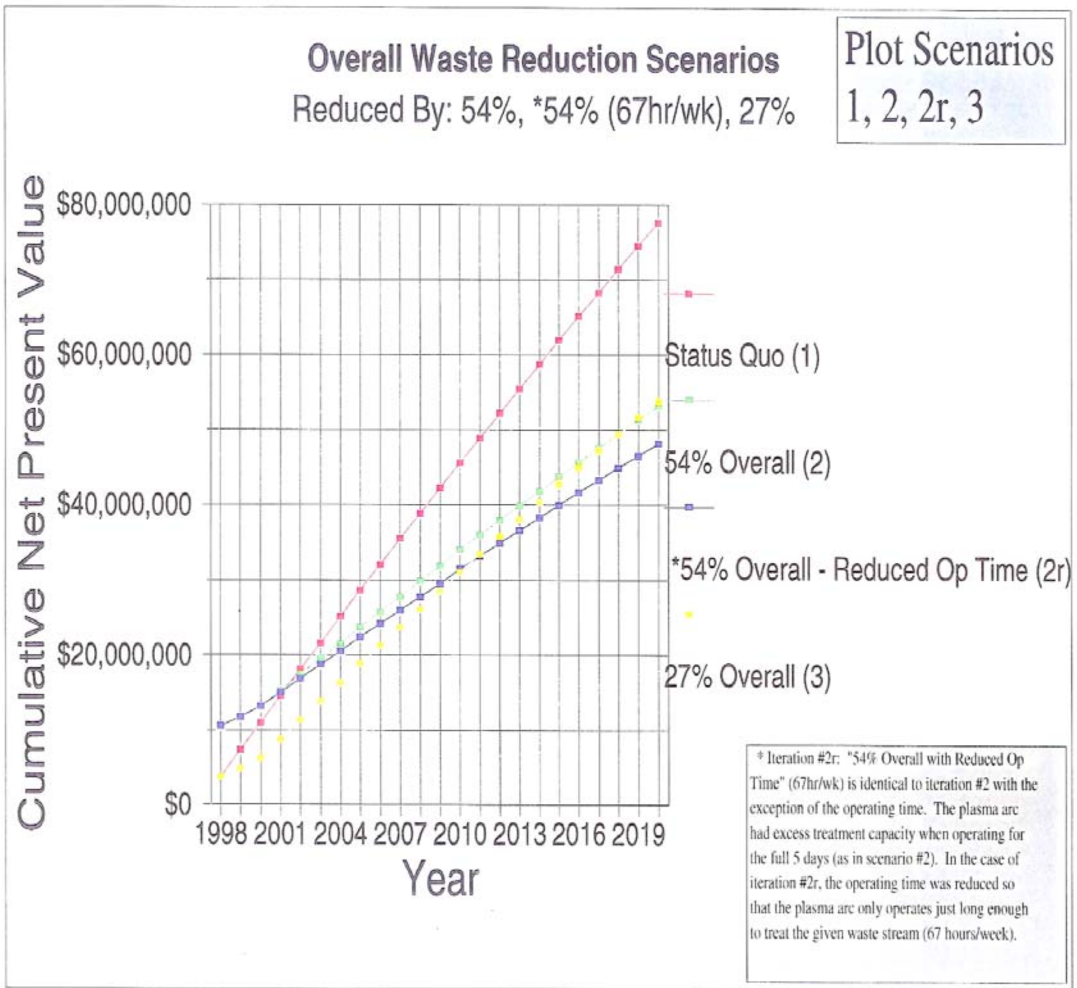

Figure 5. Results of Economic Analysis for Scenarios 1 (Status Quo), 2, 2r, and 3.

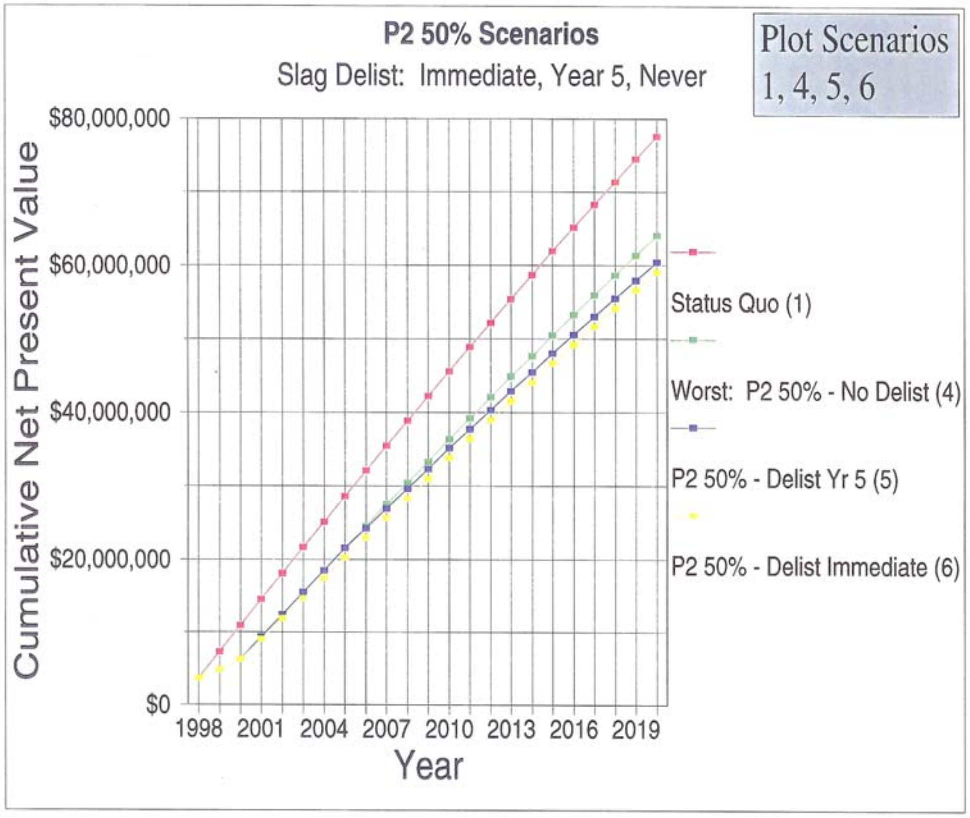

Figure 6. Results of Economic Analysis for Scenarios 1, 4, 5, and 6.

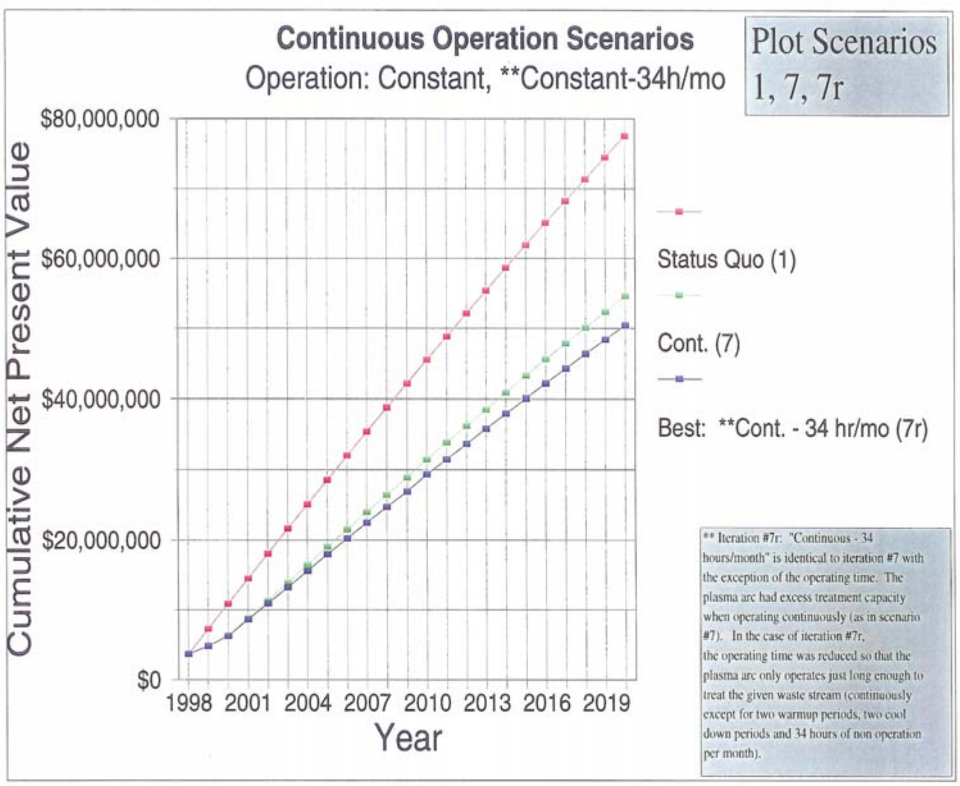

Figure 7. Results of Economic Analysis for Scenarios 1, 7, and 7r.

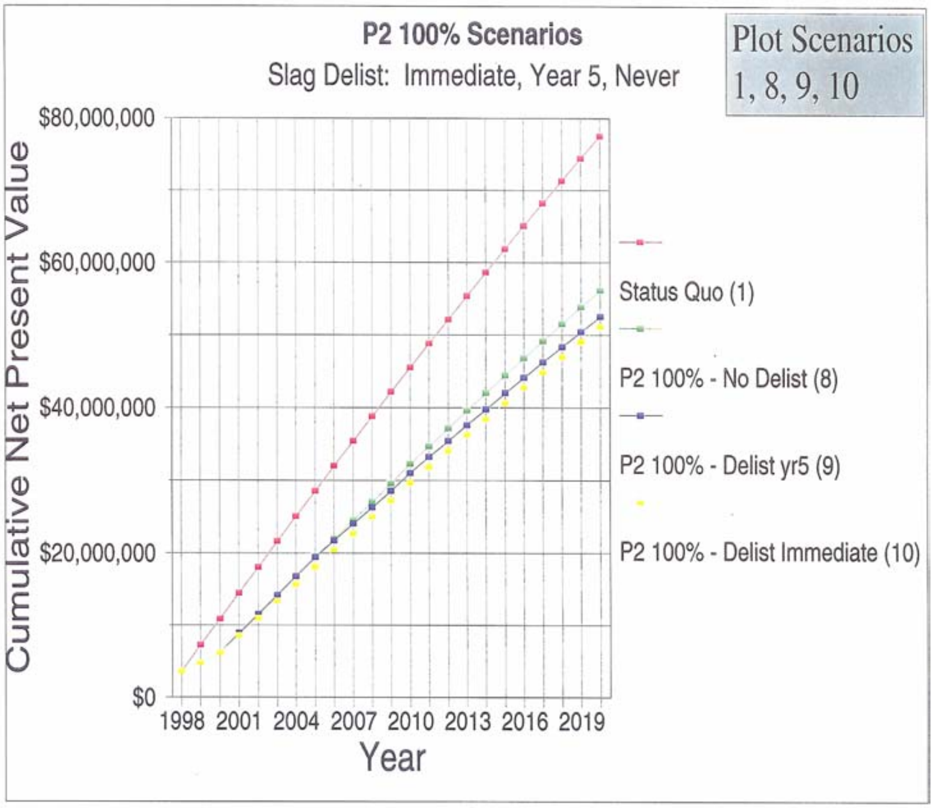

Figure 8. Results of Economic Analysis for Scenarios 1, 8, 9, and 10.

As indicated in Section 5.1, the total amount of waste generated in FY 1998 was 1,103,000 kg (1,103 metric tons), and the total cost of handling and disposing of the HW was approximately \$3,505,000, resulting in a cost-per-ton of \$3,170. Using the best-case Scenario 7r, the total annual cost of operating the PAHWTS to destroy all of the HW generated at NSN is approximately \$2,300,000, resulting in a cost-per-ton of about \$2,100. This represents an annual savings of \$1,080 per ton, or about \$1,200,000 per year for treatment of the 1,103 tons. Thus, the payback period for the \$9.4 million installed capital cost is slightly less than 8 years for this scenario. The breakdown of the \$2,100-per-ton cost of operating the PAHWTS is provided in Table 8.

Table 8. Breakdown of Operating Cost for PAHWTS per Metric Ton for Annual Treatment of 1,103 Metric Tons of HW under Scenario 7r.

Item	Quantity	Unit Cost	Total Cost
Labor			\$851.00
Amortization			\$427.00
Slag Disposal (delisted)			\$50.00
Stack Emissions Testing			\$91.00
Equipment Maintenance			\$181.00
Electricity	3.6 MWh	\$65.00	\$234.00
Nitrogen	1,200 m^3	\$0.09	\$108.00
Oxygen	1,200 m^3	\$0.09	\$108.00
Wastewater Disposal	1,250 l	\$0.04	\$50.00
TOTAL			**\$2,100.00**

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

Results of the economic analysis show that the PAHWTS would provide a savings for both the 5-day-per-week operation and the continuous operation scenarios, although clearly the most cost-effective method for operating the system is continuous. If insufficient waste were to be generated to permit continuous operation for 365 days per year, then the most efficient method would be to accumulate waste such that the system could be operated for (as an example) 21 consecutive days, then shut down for the remaining 9 days of the month. The analysis also indicated that even if NSN is successful in significantly reducing the amount of waste generated, there still would be substantial savings over the 20-year period by using the PAHWTS for treatment of the remaining HW.

Assumptions were made in the economic analysis that could not be verified because the PAHWTS was never installed or operated at NSN since CNRMA decided to withdraw support for the project. The following reasons were given for this withdrawal.

- The environmental budget at NSN was declining and funds were not available for the building modifications and ancillary equipment (e.g., transformers, gas supply systems and bridge crane).

- Even though the TAMS Consultants, Inc. economic analysis showed a cost benefit even with a substantial reduction in the amount of waste being generated at NSN, CNRMA believed that such reductions would occur and that the viability of the PAHWTS for destroying waste would therefore be questionable. CNRMA was not willing to consider importing waste from other military facilities in the Norfolk area.

6.2 PERFORMANCE OBSERVATIONS

Since the PAHWTS was never installed at NSN, many implementation issues associated with putting the system into operation never materialized. As described in Section 4, the performance of the system during the FIT was marginal, with several feed problems and some of the emissions not meeting the MACT Standards. However, considering the very small amount of materials treated during the FIT, the performance was sufficient such that there was a perceived high probability that with adequate shakedown testing, the PAHWTS would meet both the feed and emission requirements.

6.3 SCALE-UP ISSUES

The PAHWTS was a full-scale system and after successful completion of the period of operation under the RD&D permit, no further modifications of the system or other scale-up issues were anticipated.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Another obvious issue is public acceptance of the technology for treating HW. A good indicator of this is the public scoping meeting held in May 1996 near NSN where presentations were made about the project. Approximately 50 people attended this meeting, and there was virtually no opposition voiced to placing the PAHWTS at NSN. In addition, in the summer of 1996, a front-page article appearing in the principal Norfolk newspaper describing the project did not generate any public opposition. Even with the apparent favorable public acceptance of the PAHWTS in Norfolk, it is clear that if attempts are made to place these types of systems onto other government installations, good public relations are essential. It will also be important to differentiate plasma arc technology from incineration in order to gain public acceptance.

6.5 LESSONS LEARNED

The most significant source of delay in executing the project was preparing the NEPA documentation. Approximately 5 years were spent attempting to complete a Draft EIS and push it through the various approval authorities at CNRMA, CINCLANTFLT, and the Office of the Chief of Naval Operations. Each organization requested revisions, and the revised document had to be forwarded through the complete chain-of-command again, resulting in additional revisions. Finally, in 2001 it was decided to abandon the EIS process and prepare an EA which would require fewer steps in the approval chain. Thus, it was learned that the decision to pursue an EIS or EA should be made at the beginning of this type of project. Then all appropriate persons in the approval chain-of-command should be apprised of the project and a firm timeline established for completing the process.

6.6 END-USER ISSUES

A key issue associated with the decision to install the PAHWTS at NSN was the potential impact of a successful pollution prevention program within the Navy resulting in significantly reduced quantities of HW being generated. It should be noted that from 1998 to 2001, there was very little reduction in the quantity of HW generated at NSN.

- 1998: 2,426,000 lb (1,103,000 kg)
- 1999: 2,419,000 lb (1,099,000 kg)
- 2000: 2,722,000 lb (1,237,000 kg)
- 2001: 2,446,000 lb (1,112,000 kg)

A principal reason of CNRMA for not continuing the project was the anticipated success of the Navy pollution prevention program in reducing the amount of HW requiring disposal, but it is clear that, at least through 2001, such reductions were not realized. If other military facilities are encountering a similar situation, this project indicates that commanders should be more receptive to technologies that reduce the burden of waste disposal.

Other issues in support of using the PAHWTS for on-site destruction of HW include:

- Liability related to off-site disposal is eliminated.
- Fewer HW landfills would be required.

- The public would not have HW transported over public roadways.
- The threat of terrorist actions against HW transporters would be eliminated.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The project was successful in developing a complete EA that would have led to a finding of no significant impact. An air permit application was developed and submitted to the State of Virginia, which led to the issuance of a permit to construct and operate. A RCRA RD&D permit application was prepared and submitted to the State of Virginia, but the project was canceled before the permit was issued.

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APPENDIX A

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